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TIME EFFECTS ON THE STRESS/STRAIN PROPERTIES OF CLAY CONSOLIDAT--ETC(I)
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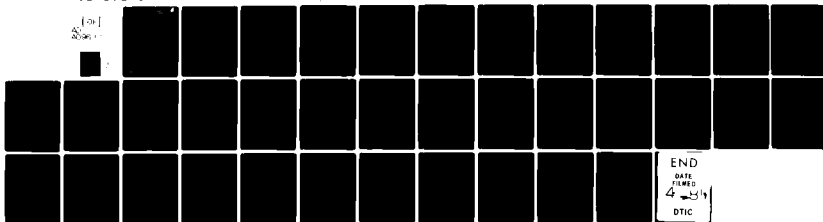
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TIME EFFECTS ON THE STRESS/STRAIN PROPERTIES
OF CLAY CONSOLIDATED IN THE LABORATORY

Final technical report

by

Roland Pusch

November 1980

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SUMMARY

"Reserve" strength properties are characteristic of many soft clays which are normally consolidated from a geological point of view. The phenomenon has been assumed to result from creep processes in the course of secondary consolidation. If the strengthening processes associated with creep are responsible for the "reserve" strength, they should result in a successive shift of the energy barriers to interparticle slip to higher values and this was investigated in the present study.

Samples of natural, undisturbed as well as artificially produced clays were consolidated under a pressure corresponding to the double consolidation pressure and were then left to rest under a reduced pressure and drained conditions. After various periods of rest, the samples were sheared under undrained conditions and it was observed that the strain at failure decreased and that the shear modulus increased with the time lapsed. This can be explained in terms of a shift of the energy spectrum to higher barrier values, the most probable physical equivalent being an improved number and strength of re-formed particle bonds, primarily of the clay/water-complex type.

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INTRODUCTION

It is of great practical significance that organic-poor natural clay, which is normally consolidated from a geological point of view, often exhibits "reserve" strength properties, while a sample of the same clay consolidated under an increased pressure in the laboratory does not have this property (Fig. 1). According to BERRE & BJERRUM, 1973, the reserve strength, which is also manifested by brittle

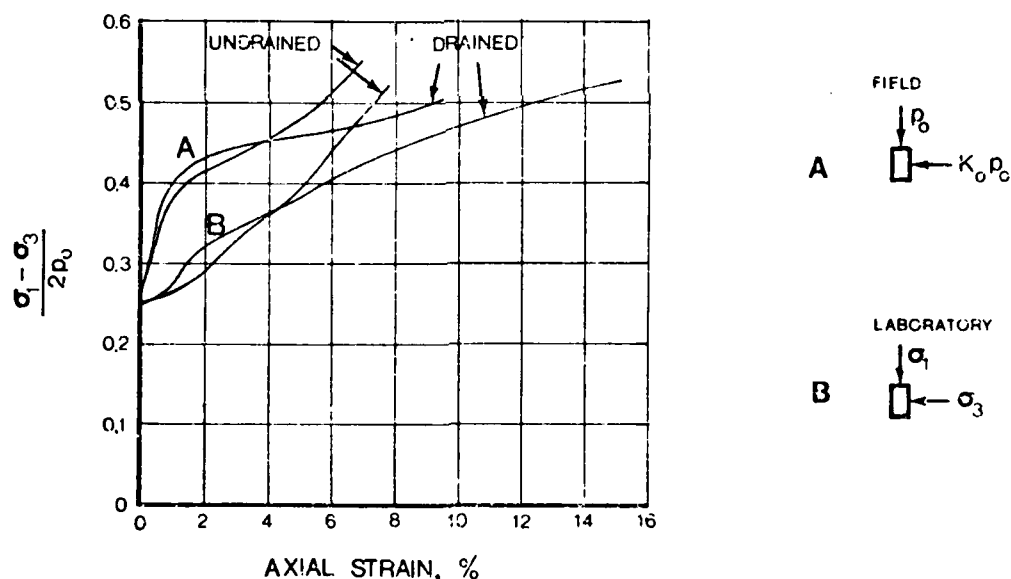


Fig. 1. "Reserve" strength of sample consolidated under in-situ stress conditions (p_0 and $K_0 p_0$, curves A) in comparison with sample consolidated under increased pressure ($2.5 p_0$ and $2.5 K_0 p_0$, curves B). (After BERRE & BJERRUM).

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behavior similar to that of cemented clays, is caused by a creep of the clay particles into stable positions in the course of the secondary consolidation in nature. The observed effect is akin to the strengthening microstructural processes which yield retardation of the creep in shear at low and moderate deviator stresses. Creep theory will therefore be used as a basis of this study.

THE MINERAL/WATER/ELECTROLYTE SYSTEM

The physical state of the pore water

Energy is released in the course of the adsorption of the first 1-3 layers of water molecules onto surfaces of dry clay particle. This is partly due to the hydration of exchangeable cations but also of the surfaces of minerals. The exchangeable ions seem to hydrate without appreciable dissociation (LOW & MARGHEIM, 1979), and it is therefore reasonable to believe that the first few layers of molecules are firmly bound to clay minerals.

Substantial evidence has in fact accumulated pointing to a very strong fixation of the first molecule layers and this affects interparticle and intralamellar spacings. The writer's current study of the swelling pressure of Na bentonites shows that maximum net repulsion and non-reversibility do not appear even at an average intralamellar distance of about 10 Å, such as has also been suggested as the approximate decay length for a presumably "steric" stabilizing water structure on mica surfaces (DERJAGUIN & CHURAEV, 1974) ISRAELACHVILI & ADAMS, 1978). Recent studies of proton relaxation of water adsorbed on silica glass surfaces (ALMAGOR & BELFORT, 1978) and experimental determination of the amount of nonfrozen water in frozen illitic clays (PUSCH, 1979) support the view that one or a few water molecule layers are firmly adsorbed on most silica mineral surfaces.

The degree of structural order of such "vicinal" water does not necessarily have to be high, as DROST-HANSEN (1969) has pointed out. His water model consists of three zones with different structural and electrical properties (Fig. 2). Zone A comprises densely spaced, "fixed" water molecules. The intermediate B-zone, is characterized by a very low degree of ordering and by low viscosity; zone C consists of normally structured, "free" water.

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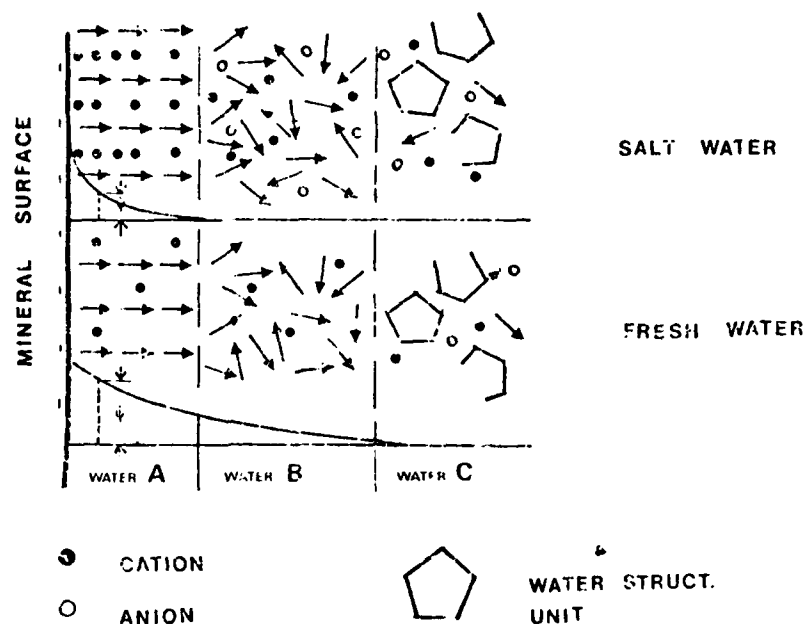


Fig. 2. Schematic picture of DROST-HANSEN's water model combined with electrical double-layers.

Studies of the nuclear relaxation properties of water in illitic clays have disclosed short spin-spin coherence times which, in fact, suggests a high proton mobility and thus some degree of structural order (PUSCH, 1970). The results of the silica glass surface study by ALMAGOR & BELFORT show that this order occurs in the vicinal water.

Particle interfaces

There are several indications that the interparticle distances are comparatively small in natural illitic sediments; consolidation, resulting from the overburden in nature, implies such a close approach of load-transferring particles. Thus, the energy required to expell the last few layers of water when parallell clay plates are pressed together should be considerable. In fact, the pressure required to remove

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one monomolecular layer may be as much as $4 \cdot 10^5$ kPa (4000 atm) according to van OLPHEN, 1967. Although grain pressures may become very high it is unlikely that parallel plates get forced together to form mineral/mineral contacts at shallow and moderate depths in nature. Instead, with such associations, the interparticle distance will be adjusted so as to comply with an equilibrium between interparticle attraction from the hydration energy at small interparticle distance or by electrical double-layers at larger distances, on the other hand. At effective stresses lower than 100 kPa the average equilibrium interparticle distance between well oriented clay plates in illite clay is at least 50-75 Å.

A close approach between particles, which may even result in mineral/mineral contacts, is most readily established with particles arranged edge-to-edge and, possibly, edge-to-face, for edges are the least hydrophilic sites and also because grain pressures may than be exceptionally high. All three modes of particle association are theoretically possible because of the large variety of bonding mechanisms. Studies of the microfabric (PUSCH, 1970) have shown that the dominant association types within particle aggregates are in fact edge-to-face and edge-to-edge arrangements (Fig. 3). The spatially varying grain pressure and attraction/repulsion forces balance, as well as the variation of the orientation of adjacent particles, imply a spectrum of interparticle distances (Fig. 4) and therefore also of the strength and local strains of particle bonds.



Fig. 3. Transmission electron micrographs showing edge couplings are seen in all the micrographs (PUSCH, 1970). The central part of c) shows an edge-to-face contact as well.

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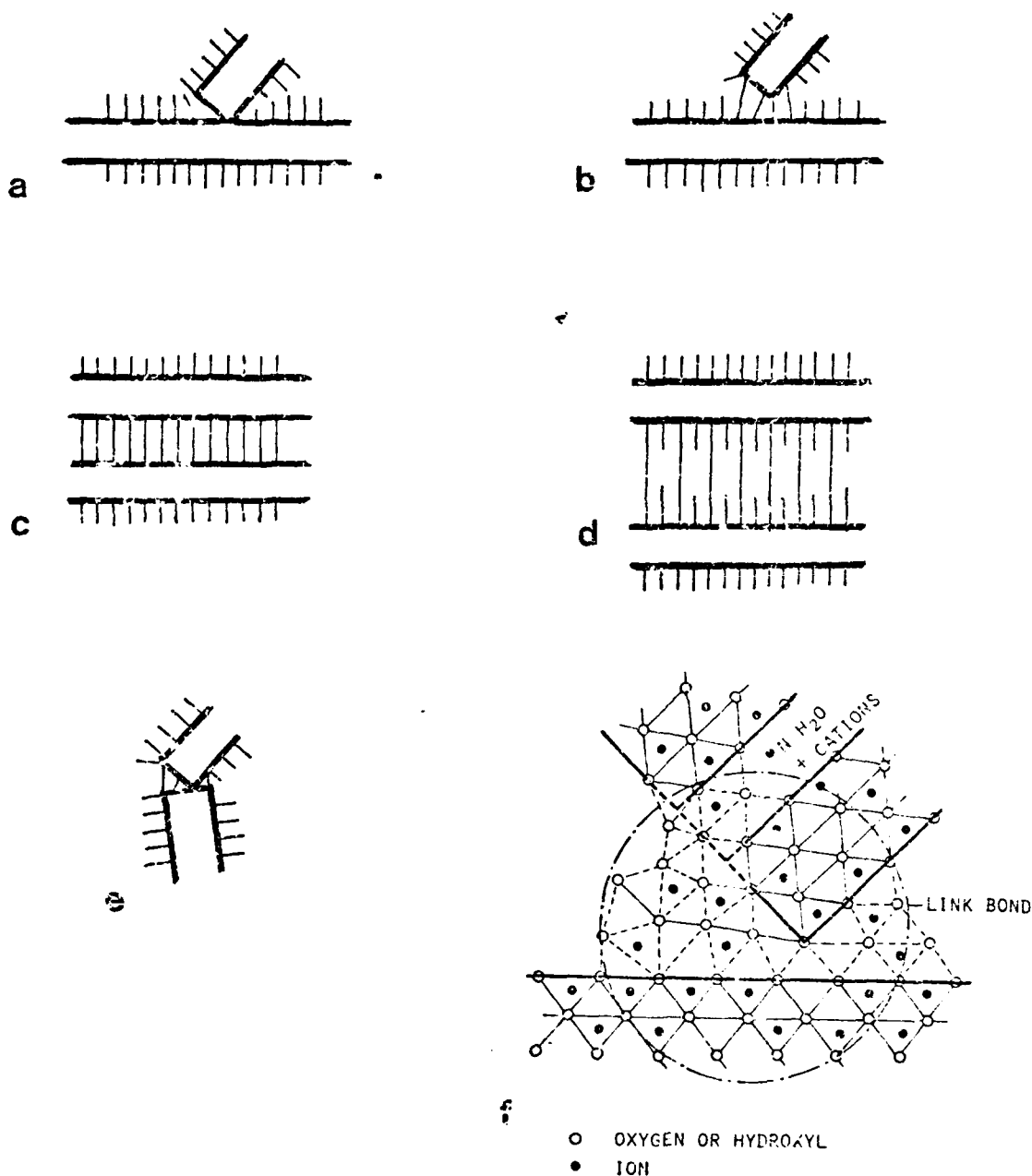


Fig. 4. Schematic contact types in clays
 a) Mineral/mineral edge-to-face contact
 b) Water interface edge-to-face contact
 c) Close face-to-face arrangement
 d) Expanded face-to-face arrangement
 e) Edge-to-edge contact
 f) Mineral/water lattices in montmorillonite

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Clay microstructure

In recent years it has become generally accepted that natural, soft, illitic clays consist of more or less randomly arranged groups of particles rather than of single minerals as proposed in early concepts of clay fabric (Figs. 5 and 6). There is extensive evidence that face-to-face grouped particles - "domains" - are formed by local overstepping as illustrated in Figs. 7 and 8, while the major feature of undisturbed, soft, illitic clay usually is that of dense aggregates (crumbs), either supporting each other or being connected by links or bridges of small particles (BOWLES et al. 1969, PUSCH, 1970, BENNET et al. 1977). Such local overstepping results from shearing as well as from consolidation. The process of domain formation is fundamental in the evolution of the creep and in shear failure (PUSCH, 1980).

Particle displacement requires that interatomic or intermolecular forces be overcome. Domains are probably formed by simultaneous rupture of several bonds, and macroscopic shear failure must involve rupture or slipping of all bonds along the shear plane. Creep at low or intermediate stresses, on the other hand, may result largely from displacements due to individual atomic "jumps" or multi-bond slip.

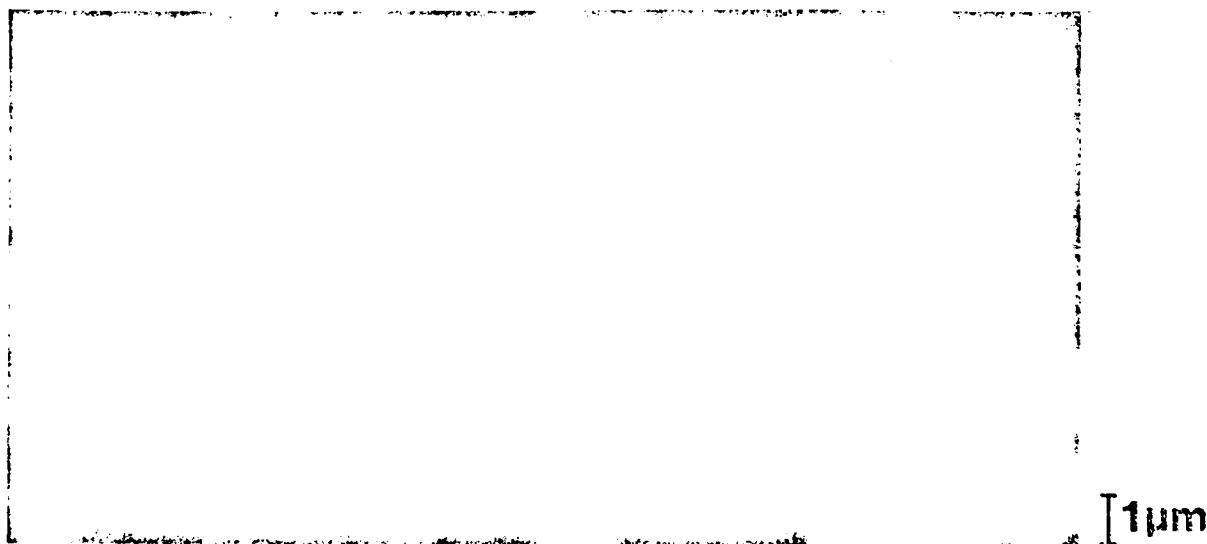


Fig. 5. Aggregation of illitic clay. The picture shows electron micrograph of a clay/water gel. The gel was isolated from the vacuum of the high voltage microscope by a closed cell (PUSCH, 1970).

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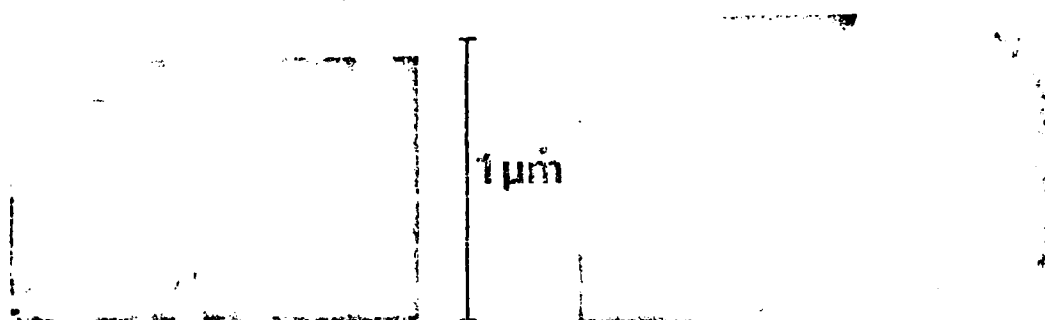


Fig. 6. Typical pattern of linked aggregates in illitic clay. Micrographs of ultra-thin sections of acrylate-treated specimens.

Simultaneous rupture of patches of H-bonds is likely in aged vicinal water, as it is probably ordered. The degree of order is assumed to rise with time following mechanical disturbance, as is indicated by the time-dependent changes of the (proton) spin-spin coherence time (JACOBSSON & PUSCH, 1972).

The atomic or molecular bond strength in mineral/mineral contacts may well be of the order of that of primary valence bonds, i.e. approximately 1-2 eV. The displacement of a contact of this type is likely to involve simultaneous rupture of a number of such bonds and it therefore represents strong particle coupling. Additionally, one has the hydrogen bonding of the firmly held water collar surrounding the mineral contact. H-bonds are of the order of 0.1-1.0 eV and, as in aged contacts, a displacement probably involves simultaneous rupture of several bonds, the vicinal water can be assumed to contribute to the interparticle adhesion.

Where particles are separated by water at the points of contact, the strength is lower. Aged contacts with a one-water-molecule "lattice" interlayer may still be fairly

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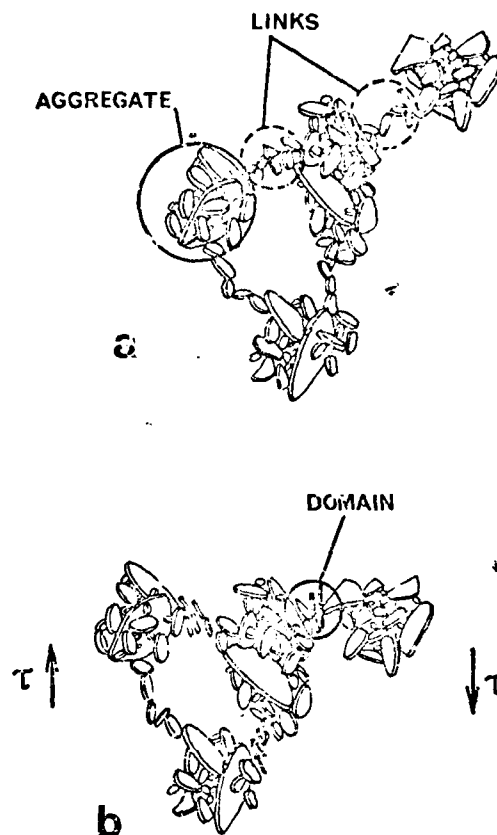


Fig. 7. Formation of domains (b) by local overstressing of initially undisturbed network (a).

strong, but with three or more interlayers there is a large drop in strength. In freshly formed contacts of the face-to-face type, i.e. in young domains, individual shear "jumps" formed by rupture and reformation of H-bonds are expected to occur with a relatively low activation energy. If DROST-HANSEN's model is valid, slip will take place easily if the interparticle distance exceeds about 25 Å.

Where cementation has taken place, the coupling between adjacent particles is, of course, very strong. There are reasons to believe, however, that also in virtually non-cemented clays the solubility of minerals pressed together

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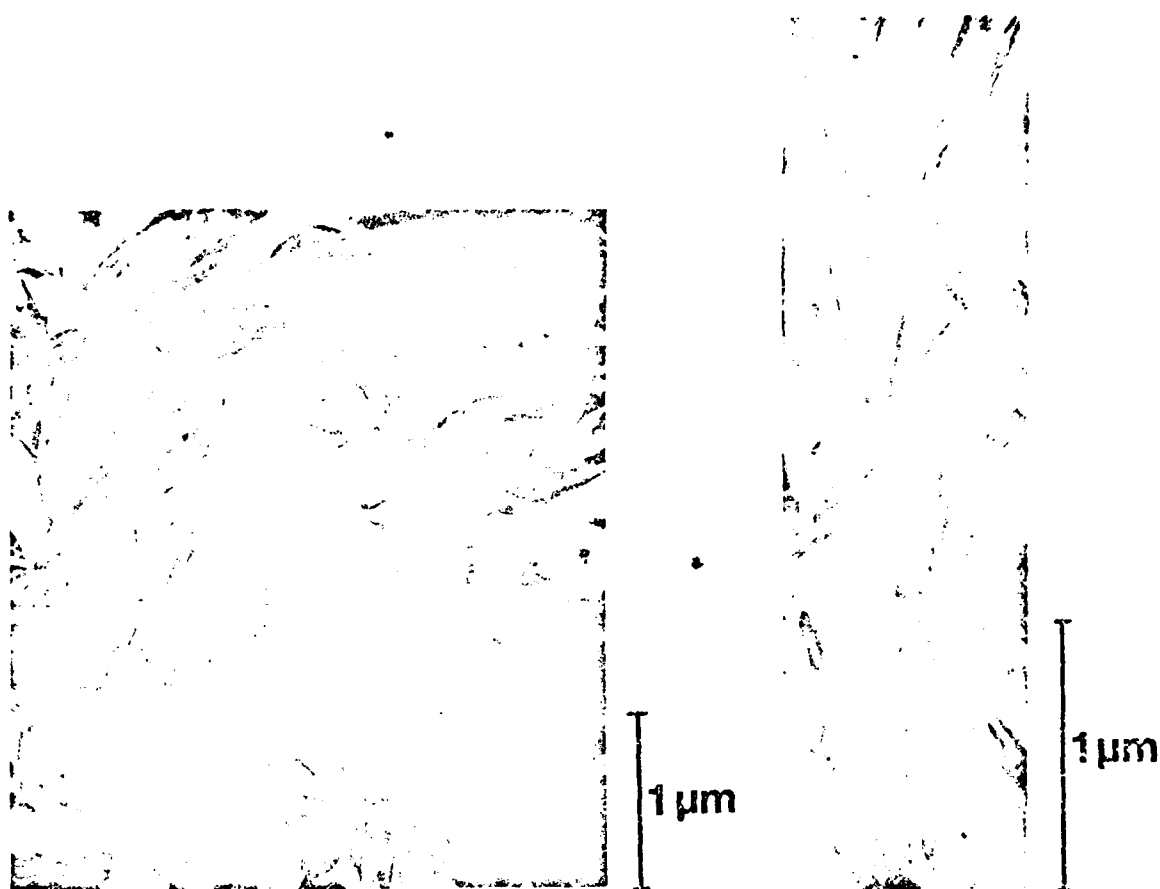


Fig. 8. Left picture: Domain-rich heavily overconsolidated Silurian clay. Right picture: Domain formation in very soft Quaternary clay.

or simply exposed to the pore fluid may lead to local supersaturation, and thus to deposition of SiO_2 on non-stressed crystal faces. The solubility is low at low grain pressures, but it rises rapidly at higher pressures. Thus, when the grain pressure is increased from 1 MPa (10 atm) to 100 MPa the solubility increases by a factor of more than 10^4 . Such reinforcement of edge-to-edge and edge-to-face contacts may contribute somewhat to the particle coupling, and could be important in clay sediments at fairly large depths.

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CREEP EVOLUTION

Phenomenology

The preferred types of association observed in major structural units in natural, soft, illitic clays, i.e. the aggregates and linking particle groups, point to close and strong contacts. When local overstressing occurs, a fraction of the atomic bonds are broken and some contacts are interrupted. This facilitates particle displacements leading to the formation of face-to-face-grouped particles, i.e. to domains. The interparticle distances are adjusted to attain equilibria of force, which results in larger average distances than in the former intra-aggregate contacts. A certain net gain in strength may arise from the successive formation of interconnecting layers of adsorbed water; however, aged domains remain the weakest structural members in the clay. It is therefore reasonable to assume that, under the action of an external stress, further movement in the clay network takes place mainly in these units, and in the course of formation of additional domains. These units will therefore be considered here as main sources of slip in the evolution of creep: their deformation and displacements appear to result from the breaking and reforming of hydrogen bonds.

The relative weakness of the domains facilitates a rapid "initial" deformation on applying an external load. Several mechanisms combine, however, to reduce this high strain rate progressively. Firstly, deformation of the domains will induce local displacements such that stronger units will make contact and help to strengthen the structure. Secondly, the displacements may lead to the formation of new domains from bridging links which have become overstressed. If the stress level is sufficiently high, such structural damage will accumulate, and bulk failure will eventually take place. Below a critical stress level, two healing processes take place which oppose the weakening and retard the strain rate. They are connected with the strain-induced interaction of adjacent aggregates and involve micro-dilatancy and mechanical interlocking, as well as reformation of water "lattices" and establishment of new, interlinking particle groups. These processes take place when the relative movement of close aggregates has ceased, either because of interlocking or because they are temporarily not subjected to strain-inducing local stresses. The net effect of these "thixotropic" processes is probably dependent on the average strain rate. An indication of the correlated strengthening and weakening can be obtained from the sequences shown in Fig. 9.

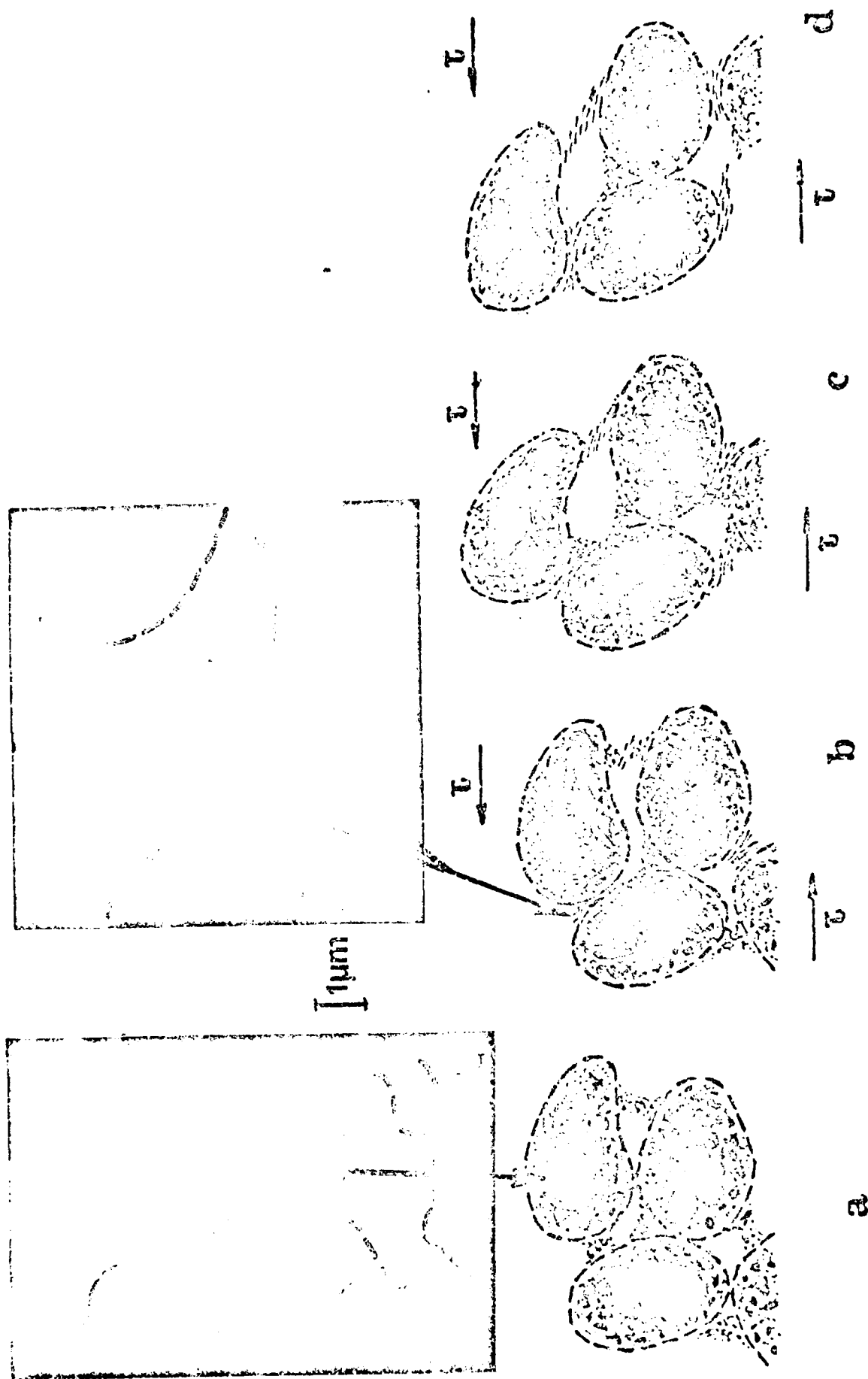


Fig. 9. Consecutive stages in the evolution of the creep of aggregated clay. (a) Before loading, (b) Shear and formation of domains at the application of the stress, (c) Formation of domains accompanied by healing and breakdown, (d) Creep failure. Micrographs show features of moist, illitic clay.

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Stress/strain model

Physical form

In formulating a realistic description of a general physical stress/strain model, it is of importance to consider the heterogeneity in stress and structure on the micro-scale, because it results in a distribution of heights of the energy barriers to slip. The energy spectrum will vary in the course of strain in shear and consolidation. Some barriers may become enhanced due, for example, to a decrease in local stress fields. Others, latent at first, may be rendered "operative" through the converse process. An appropriate model must therefore take into account not only the existence of a distribution of energy barriers, but also its change with time in the course of the evolutionary processes.

Specifically, the following features are included in the model:

1. The clay is regarded as a heterogeneous system, comprising dense, strong, structural elements (aggregates and silt particles) connected by links of various strength, i.e. potential slip units (domains) with a dispersion of resistance to deformation.
2. The application of a shear stress, or an oedometer load step, produces a certain number of slip units. Their movements and the displacements and deformations of secondarily formed slip units make the main contribution to the overall observed strain. The slip, which has the character of activated atomic or molecular jumps, can be visualized as resulting in the form of shiftings of individual atoms or molecules as well as of patches of such units. The shiftings are considered as thermally assisted passages over energy barriers driven by the external stress.
3. The slip process leads to an interaction between bigger and stronger structural elements which results in local stress relaxation and in an increase in the heights of the energy barriers for subsequent activated jumps. It is thus a "hardening" process.

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4. New links and particle bonds formed in course of the strain will also tend to strengthen the structure.
5. Regional redistribution of stresses facilitated by slip produces local stress concentrations. It will assist slip decreasing the heights of some energy barriers, and is thus a "softening" process.
6. In drained creep tests, of which the oedometer test may serve as an example, the successive approach of neighbouring aggregates or larger particles of course contributes to the shift of the energy barrier spectrum to higher values.

The general features of a stochastic model which corresponds reasonably well to the physical prototype are:

1. There is a spectrum of barrier heights for slip in the material (Fig. 10). The shape of the distribution curve reflects the microstructural heterogeneity and types of dominant bonds at different times after a stress change.
2. Each element of clay contains a certain number, $n(u, t)$, of slip units in any given interval of the activation energy range.
3. In the course of slow strain the low energy barriers are triggered early, while higher ones are activated later. Also, new slip units are formed at the lower end of the energy spectrum.
4. The model allows both for slip which, when it takes place, takes a given slip unit up against a barrier by an amount either δu higher than the previous one, or lower by the same amount.

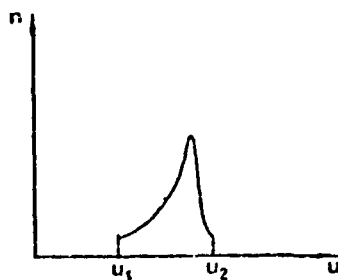


Fig. 10. Activation energy spectrum at a given time t after the onset of creep.

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Mathematical form

The derivation of a mathematical model for a particular case, which is also of interest in this context, has been outlined previously (PUSCH and FELTHAM, 1980), so only the basic steps are briefly recapitulated here.

At any given temperature only a limited energy spectrum $u_1 \leq u \leq u_2$ will be of significance in the determination of strain and strain rate. The number of potential slip units per unit volume held up at barriers of height u , is then $n(u, t) \delta u$ per energy unit, where t is time after the onset of creep, and δu one of the energy intervals into which we consider the spectrum between u_1 and u_2 .

A basic assumption is that the attempt frequency of slip $v(u)$ is given by the Arrhenius rate equation:

$$v(u) = v_D \exp(-u/kT), \quad u_1 \leq u \leq u_2 \quad (1)$$

where u is the barrier height. Here, v_D is an atomic vibrational frequency of the order of 10^{12} per second. k is Boltzmann's constant and T the absolute temperature.

If slip has been activated at a certain point in the material, i.e. a barrier has been overcome, a contribution to the overall shear is made by the associated extension of the local slip-patch and the next barrier to be encountered by the same spreading slip-zone will be either higher or lower by an average amount δu . The magnitude of δu is determined by the amplitude of the internal stress field, and by the physical nature of the barriers.

It is reasonable to allow for an equal probability of slip following an activated jump of a patch, to occur so that the next barrier encountered by the patch is either higher or lower than the previous one, and considerations analogous to those familiar from the derivation of equations of diffusion then yield, on writing n for $n(u, t)$ for the continuity equation of the process:

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$$\partial n / \partial t = D \partial^2 [n \exp(-u/kT)] / \partial u^2 \quad (2)$$

$$D = \frac{1}{2} v_D (\delta u^2)$$

For low temperatures an appropriate solution of Eq. 2 is:

$$n(u, t) \propto p \cdot \exp(-p) \quad (3)$$

$$\text{with } p = \exp(u/kT) / v_D (t + t_0)$$

where t_0 is a "structure-sensitive" constant of integration

If the passage of a slip patch through the element of dimensions L (Fig. 11) displaces the part above the slip plane over the plane below by an amount b , then the resulting shear is b/L . If a slip unit does not traverse the whole element but advances only a certain distance on activation under the influence of the local stress field, then the shear strain will be:

$$\delta \gamma = \left(\frac{b}{L} \right) \cdot \left(\frac{\Lambda^*}{L^2} \right) \quad (4)$$

where Λ^* is the area swept over by the patch in jumping to the next barrier.

If slip has been activated at a certain point, the contribution to the overall shear is given by Eq. 4, so if there are $n \delta u$ points per unit volume and unit of energy, where the barrier height is u , then in a cube of side L , the contribution $\delta \gamma_u$ due to slip of all u -units is:

$$\delta \gamma_u = \left[n(u, t) L^3 \right] \left(\frac{b}{L} \right) \cdot \frac{\Lambda^*}{L^2} \delta u \quad (5)$$

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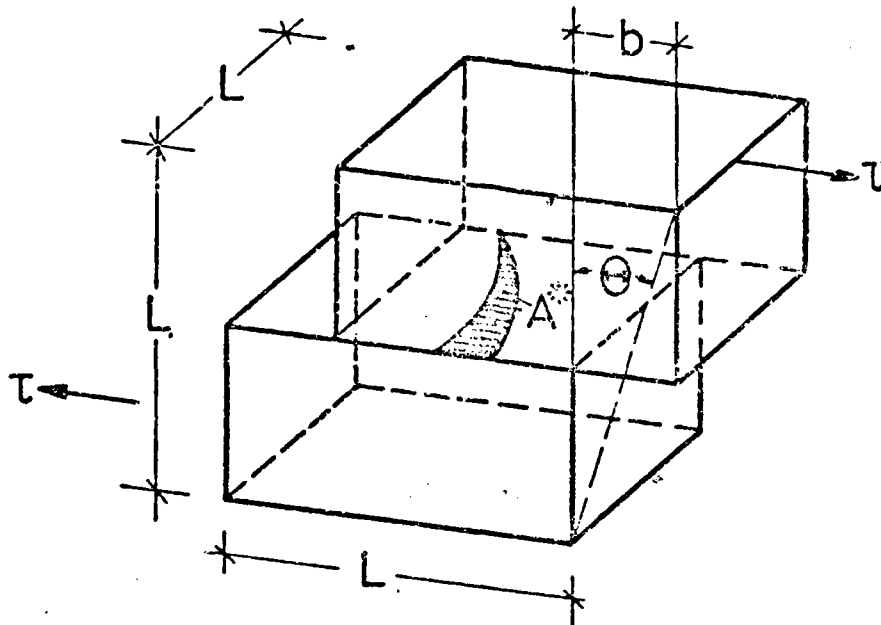


Fig. 11. Soil element with internal displacement produced by a slip. τ is the shear stress.

If the attempt frequency at all such points is $\nu_D e^{-u/kT}$ per second, then the contribution by the u -interval to the strain rate is:

$$\delta \dot{\gamma} = \nu_D b A^* n(u, t) \exp(-u/kT) \delta u \quad (6)$$

If each activated jump makes the same, average, contribution to the bulk shear strain of the specimen, then the creep rate in shear will be:

$$\dot{\gamma} = b \cdot A^* \int_{u_1}^{u_2} e^{-u/kT} \cdot n(u, t) du \quad (7)$$

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The model is thus seen to be compatible with the processes illustrated in Fig. 9, i.e. the lower end of the energy spectrum may relate mainly to the deformation of the domains, while higher barriers will be associated with more rigid components of the structure and, largely, control the creep rate at later stages of the process.

On using Eq. 3 in Eq. 7 one has (FELTHAM, 1973):

$$\dot{\epsilon} \propto (t+t_0)^{-1} \quad (8)$$

which is in fact a commonly observed relationship, t_0 usually being very small (cf. Fig. 12).

An illustration of the successive shift of the spectrum to higher barriers in the course of the creep is given by Fig. 13. It shows the result of a preliminary computer calculation using the simplified assumptions of $n(u) = \text{constant}$ for $t = 0$, and allowing for no inflow of new slip units from beyond the low u -end of the spectrum.

An approximate estimate of the magnitude of the activation energies involved can be obtained by considering Eq. 1. A reasonable value of the jump rates $v(u)$ to lead to observable creep would be of the order of $1s^{-1}$ which yields $u \sim 0.6$ eV (PUSCH & FELTHAM, 1980). Such an activation energy indeed suggests that water is largely involved in creep at ordinary temperatures and that the hardening mechanisms at least partly comprise water lattice re-formation.

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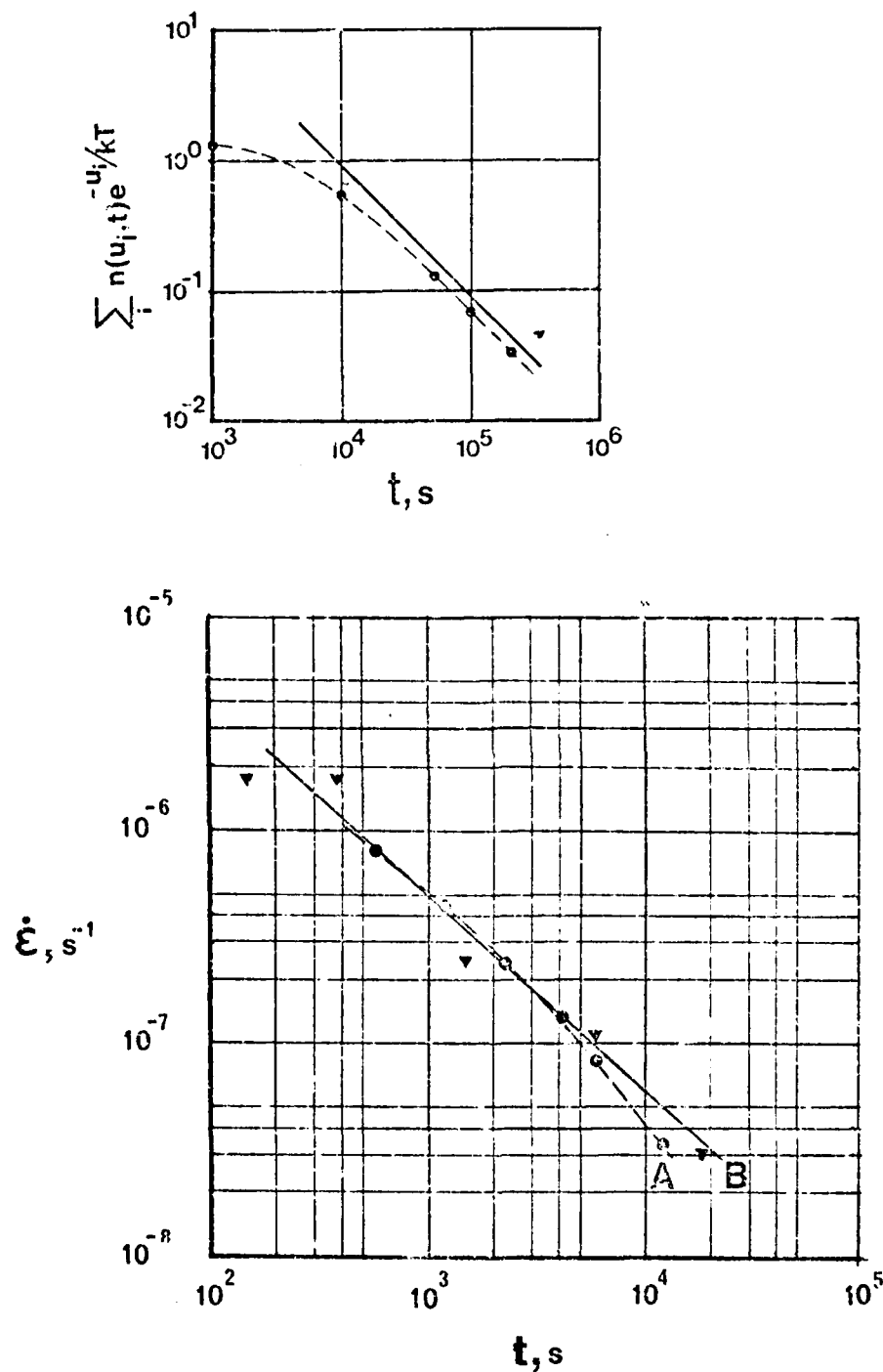


Fig. 12. Creep rate versus time after the onset of the creep. Upper picture: Theoretical relationship showed by the broken curve; the Σ -expression on the vertical axis being equivalent to $\dot{\epsilon}$. The straight line represents Eq. (8) with $t_0=0$. Lower picture: Two representative creep curves (undrained conditions) of Swedish illitic clays.

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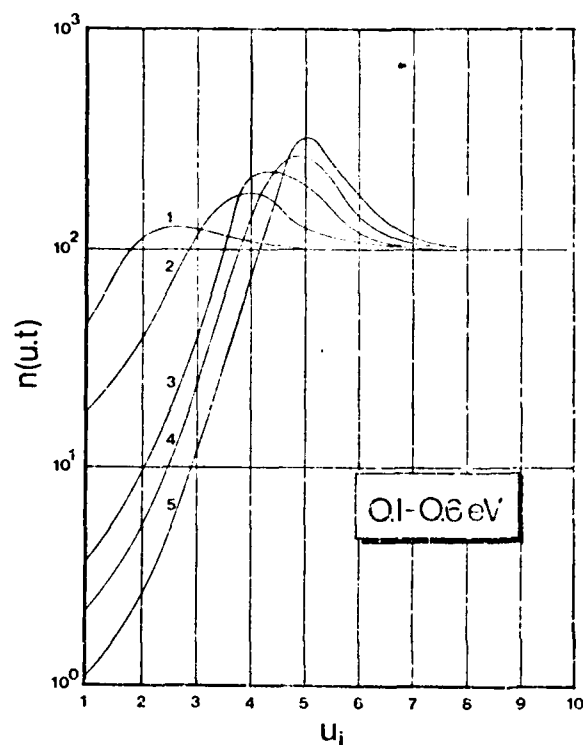


Fig. 13. Total number of slip units held up at barriers in each spectrum interval at different times after the onset of creep. 1) 10^3 s, 2) 10^4 s, 3) $5 \cdot 10^4$ s, 4) 10^5 s, 5) $2 \cdot 10^5$ s. (0.1-0.6 eV). Initial total $n(u,t)$ taken as 1.000.

EXPERIMENTAL

Object

The strengthening resulting from a net shift of the energy barrier spectrum to higher values, is naturally manifested by an increased stiffness. If it is produced by the healing processes, which lead to a retarded strain rate in the course of undrained creep, it should also be observed as a successively increased shear modulus. The same healing takes place in structurally disturbed clay which is left to rest under undrained conditions, and it should therefore be observed as an increase of the tangent modulus of any clay which is first

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structurally broken down to yield a high frequency of slip units, and then allowed to rest under drained conditions and practically constant volume for various periods of time before shearing. The main reason for the expected time effect would be the successive regrouping of small particles, which became free to move by the structural breakdown, and the re-establishment of water lattices.

The structural breakdown is preferably produced by isotropic consolidation since this affects the entire sample, while shearing may result in local zones of structural disturbance only. The period of rest cannot take place under drained conditions and with the load still on, since this would yield strengthening associated with a considerable reduction in volume. Nor can the sample be left to rest under undrained conditions since this would lead to a successive lowering of the pore pressure and thus to an increased effective stress. It was therefore decided to let the sample rest at a largely reduced pressure under drained conditions. A net increase of the tangent modulus would then reflect the strengthening produced by particle regrouping and water lattice re-formation. It was anticipated that large swelling might eventually lead to a reduced continuity of the structural network and thus to a decreased strength and tangent modulus. The initial stage of rest would probably not be very much affected by swelling, however, and this was also confirmed by the study.

Test program

A few samples of each of three fine-grained soils, one artificial and two natural clays, were isotropically consolidated in triaxial cells. The cell pressure, corresponding to twice the preconsolidation pressure or more, was applied in one increment and the volume decrease was measured so as to assure that the time of compression covered a sufficient part of the primary consolidation to achieve large structural disturbances. The cell pressure was reduced to a small fraction of its original value and the samples were then allowed to rest for various periods of time under drained conditions. The resulting swelling was determined by measuring the water uptake by means of burettes. To prevent biological activity the cells were kept in a cold chamber at 7°C throughout the storing.

The essential parameter, the tangent modulus, was determined by shearing the samples under undrained conditions at a constant axial strain rate of 0.6 % per hour. The stress/strain data were recorded by a data log system and curves

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depicting the deviator stress as a function of the axial strain were plotted to provide graphical determination of the tangent modulus. Transducers were used to record the pore pressure.

Clay materials

The artificial clay was prepared from a natural clay deposit in Heby, 100 km NW of Stockholm. It has a minus 2 μ m content of approximately 40%. Its liquid and plastic limits are approximately 40 and 18%, respectively. Air-dry clay powder was added to 35 o/oo NaCl solution to yield a thick slurry which was consolidated under a constant pressure of 100 kPa for several weeks in ordinary 50 mm sampling tubes of plastic (Fig. 14). This relatively long period of rest was chosen to

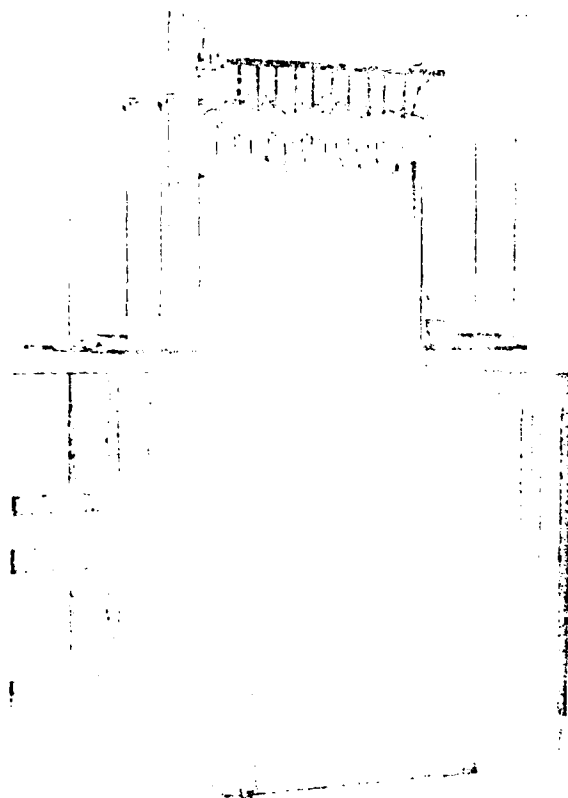


Fig. 14. Box with plastic tubes containing the artificial slurry. Plastic plugs with filter stones and steel cylinders to give the required pressure extend from the tubes. Notice the dial gauges for observing the compression. (The device was designed by BÖRGESSON, Div. of Soil Mechanics, University of Luleå).

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allow for complete pore pressure dissipation of the 120 mm long sediment cores and for the development of some natural microstructural features, such as the formation of links of small particles between aggregates and larger grains.

Such a structural pattern is typical of the two natural clays, the one from Skå-Edeby being representative of very fine-grained, late-glacial sediments deposited in fresh or brackish water, and the clay from Lilla Edet being a typical marine sediment from the Göta river valley.

The main mineralogical data of the minus 10 μ m fractions of the three clays are given in Table 1. Geotechnical data are collected in Table 2.

Table 1. Dominant minerals of the minus 10 μ m fractions.

Clay	I	Chl	K	Q	F	H	C	S
Artificial	++	+	+	+	(+)	+	(+)	+
Skå-Edeby	+++	+	+	+	+	-	+	(+)
Lilla Edet	+++	(+)	+	++	+	+	-	-

I = Illite	K = Kaolinite	F = Feldspars
Chl = Chlorite	Q = Quartz	H = Heavy minerals
C = Calcite	S = Smectite	

+++ Dominant	+	Moderately abundant	-	Absent
++ Abundant	(+)	Slight amount		

Table 2. Geotechnical data

Clay	ρ t/m ³	w %	w _P %	w _L %	τ_{fu} ¹⁾ kPa	s _t	i _c ²⁾ %	g _o ³⁾ %	Precons. pressure kPa
Artificial	1.86-1.90	34.8-36.3	19	40	-	-	40	1	100
Skå-Edeby	1.48	96-108	29	98	8.5	13	77	0.5	35
Lilla Edet	1.59	69-75	27	46	15	155	76	1	75

1) Swedish cone penetration test 2) Clay content 3) Organic content

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Performance and results

Artificial clay

Four artificially produced clay samples were isotropically consolidated in triaxial cells under a pressure of 200 kPa (Fig. 15). The consolidation was found to require 1 week before the pore pressure had dissipated. All the samples were then left to rest under drained conditions and an isotropic, total pressure of 25 kPa, which produced swelling and water uptake. The swelling, which amounted to 2.5% at maximum, continued throughout the period of rest. The time of rest was 1, 10, 30, and 120 days, respectively, and the samples were then sheared.

The shearing yielded stress/strain curves of the type shown in Fig. 16. In all the tests the pore water pressure increased to approximately 5 kPa at 1% axial strain and then dropped to zero at approximately 5% axial strain.

The strain at maximum deviator stress was clearly related to the time of rest, indicating a rest-induced stiffening. Also, the tangent modulus $E = \partial(\sigma_1 - \sigma_3) / \partial \epsilon_1$, where ϵ_1 denotes axial strain, increased with the time of rest as shown by Table 3, the values referring to the shear stress $\tau = 1/2 (\sigma_1 - \sigma_3) = 15$ kPa.

Table 3. Tangent modulus of the artificial clay as a function of the time of rest

Time of rest, days	τ_{\max} kPa	E, MPa
1	46.5	6.7
10	45.5	7.0
30	44.6	8.9
120	42.8	9.5

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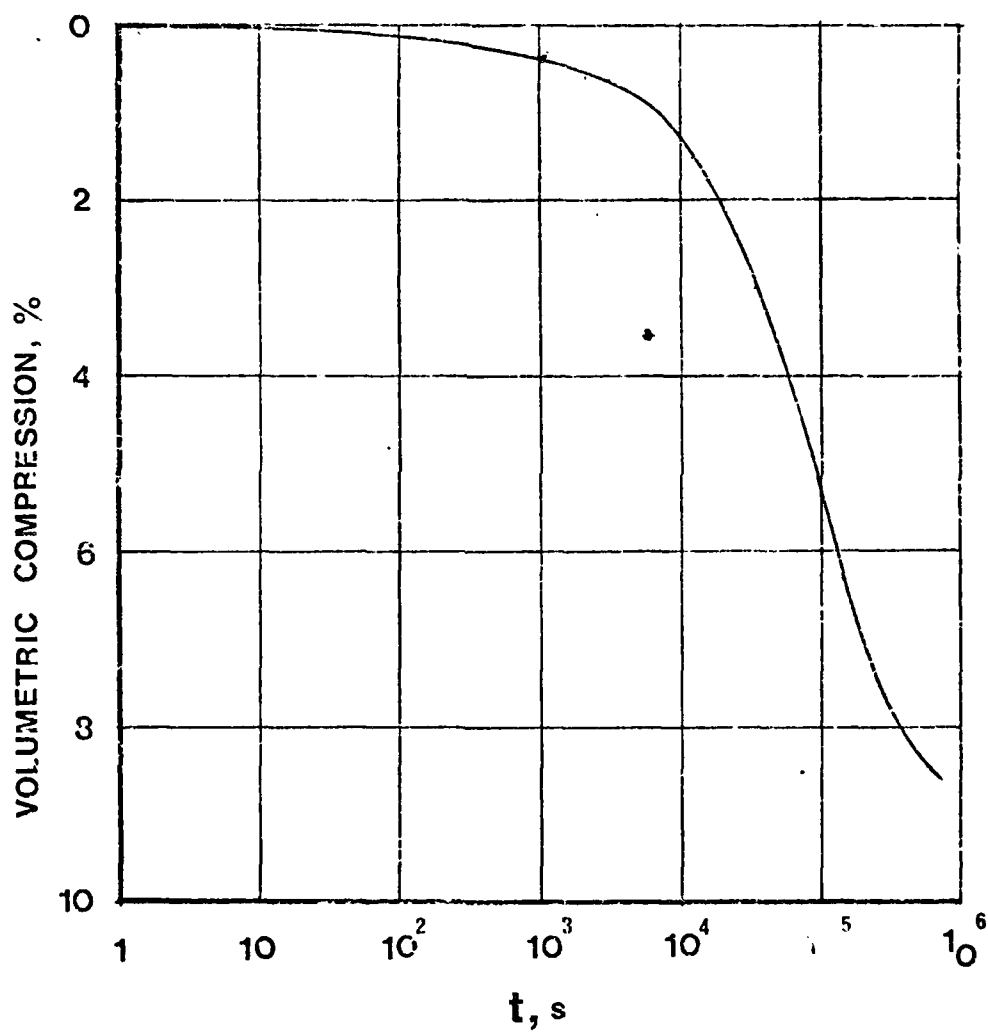


Fig. 15. Volumetric compression versus time of the artificial clay for $\sigma = 200$ kPa.

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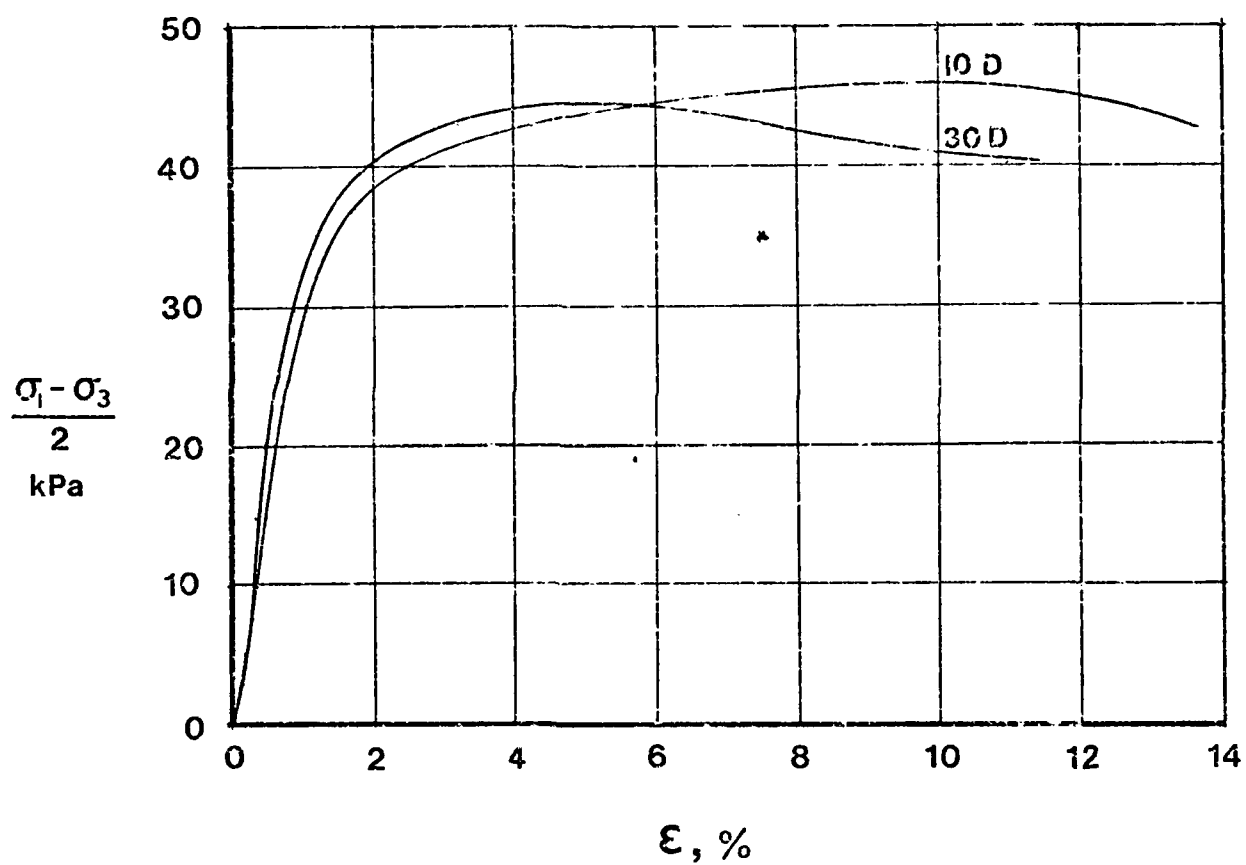


Fig. 16. Typical stress/strain plots of the artificial clay.

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The slight reduction of the shear strength with the time of rest is related to the water uptake and associated swelling, which affects the continuity of the microstructural network. The water uptake is illustrated by Table 4 which shows the water contents of the sheared samples.

Table 4. Water content of sheared artificial samples. These were divided into 6-9 parts to check the uniformity of the water distribution.

Time of rest, days	w, %									w _{average} %
	w ₁	w ₂	w ₃	w ₄	w ₅	w ₆	w ₇	w ₈	w ₉	
1	28.05	27.77	28.34	28.47	28.31	28.17	27.78	27.99	-	28.1
10	28.78	28.64	28.98	29.14	29.14	29.16	28.93	28.72	29.03	29.0
30	28.49	29.21	29.19	29.40	29.39	28.86	-	-	-	29.1
120	28.95	29.04	29.33	29.37	29.40	29.09	28.94	29.38	-	29.2

The very slight variation of the water content of each sheared sample illustrates the high degree of uniformity obtained by the applied preparation technique.

Skå-Edeby clay

Four samples from 5 m depth at Skå-Edeby were consolidated for 10 days under a pressure of 100 kPa, the volumetric compression being approximately 25%. The samples were then left to rest under drained conditions and an isotropic, total pressure of 25 kPa, which produced swelling and water uptake. The time of rest was 1, 10, 30 and 100 days respectively, and the samples were then sheared.

A typical set of stress/strain curves is shown in Fig. 17. In these tests the pore water pressure increased to approximately 12 kPa at 3% axial strain and dropped successively at larger strain. It approached 2 kPa at an axial compression of 12%.

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As in the case of the artificial clay, the tangent modulus increased with the time of rest as shown by Table 5, the values referring to the shear stress $\tau = 1/2(\sigma_1 - \sigma_3) = 8$ kPa. Similarly, the shear strength was found to drop successively.

Table 5. Tangent modulus of Skå-Edeby clay as a function of the time of rest

Time of rest,	τ_{\max}	E_t
days	kPa	MPa
1	31.7	3.7
10	30.4	4.3
30	28.5	4.6
100	27.5	4.2

The Skå-Edeby test results indeed illustrate the difficulty of using natural soils in systematic testing of soil properties. Thus, the sample which had rested for 100 days, certainly represents a discrepancy. While the artificial clay samples were sufficiently equal to permit a direct comparison of their tangent moduli, this is not the case for the Skå-Edeby samples as illustrated by Table 6, which shows the water content of the sheared samples.

Table 6. Water content of sheared Skå-Edeby samples. These were divided into 5-8 parts to check the uniformity of the water distribution.

Time of rest, days	w, %								w_{average} %
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	
1	66.4	62.2	66.6	70.8	61.1	-	-	-	66.8
10	62.3	62.2	61.2	65.0	62.0	-	-	-	63.0
30	-	-	-	-	-	-	-	-	66.2
100	66.6	69.4	71.6	71.3	73.1	73.1	75.1	72.6	71.6

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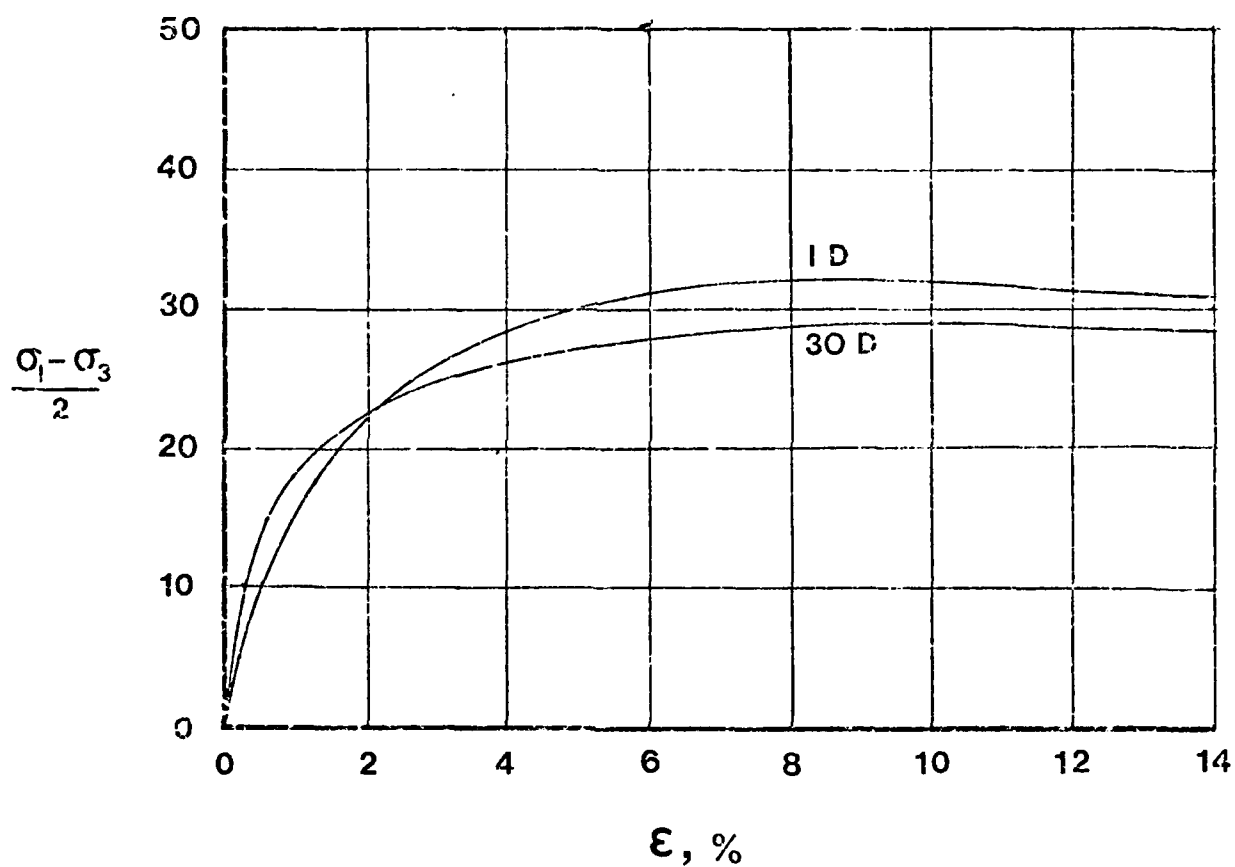


Fig. 17. Typical stress/strain plots of the Skå-Edeby clay.

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A safe interpretation should involve the samples which had rested for 1 day and 30 days, respectively, since they had practically the same water content. If these two samples are compared, we observe the same tendency as indicated by Table 3. As concerns the sample which rested for 100 days it is concluded that the relatively high water content explains the unexpectedly low tangent modulus.

Lilla Edet clay

Three samples from approximately 10 m depth at Lilla Edet were consolidated for 1 day under a pressure of 150 kPa, the volumetric compression being 15-20%. The samples were then left to rest under drained conditions and an isotropic, total pressure of 20 kPa, which produced swelling and water uptake. The swelling amounted to 3-3.5%.

The time of rest was 1, 4, and 34 days, respectively, and the samples were then sheared.

The stress/strain curves showed a marked shape change when the time of rest increased. It is illustrated by Fig. 18, which also confirms that the most obvious tangent modulus growth is observed for low deviator stresses.

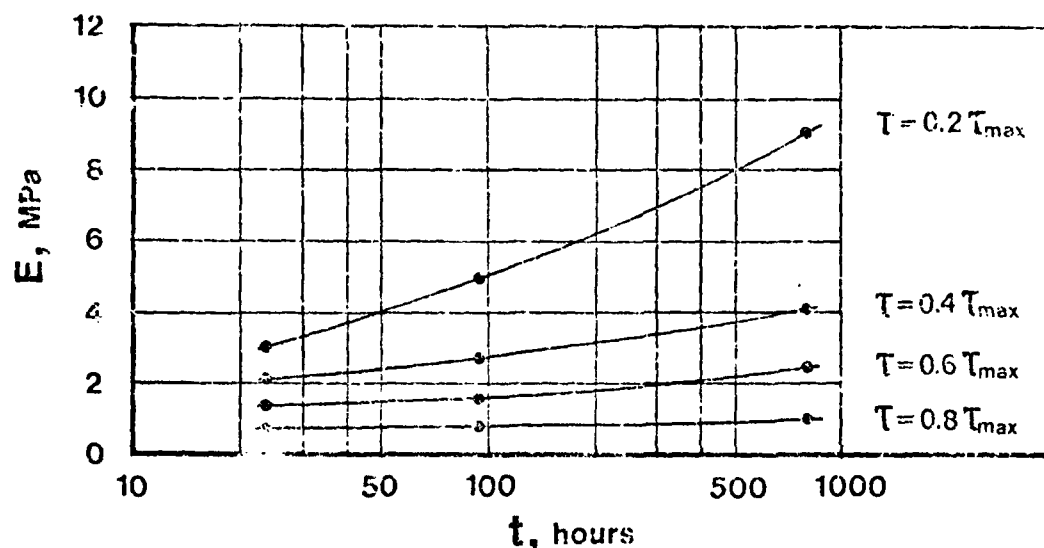


Fig. 18. The tangent modulus as a function of the time of rest for the Lilla Edet soil. 1) $\tau = 0.02 T_{max}$, 2) $\tau = 0.04 T_{max}$, 3) $\tau = 0.06 T_{max}$, 4) $\tau = 0.08 T_{max}$.

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The time-dependence of the tangent modulus shows the same trend as that of Table 3 but again, we have to consider the actual differences with reference to the water content (cf. Table 7) to be able to draw safe conclusions. The very similar water contents of the samples which had rested for 4 and 34 days, respectively, justify the conclusion that the tangent modulus increases considerably with the time of rest. The relatively low water content of the sample which had rested for one day only, should suggest a rather high tangent modulus, but the fact that the actual value was the lowest recorded, indicates that the time of rest largely determines the growth of this modulus.

Table 7. Water content of natural (w_n) and consolidated (w_c) samples.

Time of rest,	w_n	w_c	
days	%	%	
1	68.7	56.4	
4	77.8	63.6	
34	74.0	62.4	

DISCUSSION AND CONCLUSIONS

It follows from all the tests that stiffening is produced in clays which rest under practically constant volume conditions after structural disturbance. This means that the energy spectrum shifts to higher barrier values and, thus, that successive strengthening of the clay/water network takes place. It is a matter of thixotropic strength regain which is produced in any clay sediment or laboratory sample which is allowed to rest after structural disturbance.

The stiffening must be related to a successive change of the number, type or properties of the particle bonds and it seems reasonable to assume that the microstructural rearrangement suggested in Fig. 9. is responsible for the strengthening.

If we consider the conditions in nature, where secondary consolidation is associated with a reduction in volume in contrast with the laboratory test conditions, there is a net increase in peak shear strength as well. The origin of the reserve strength and brittle behavior observed by BERRE & BJERRUM is then readily explained by the microstructural pro-

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cesses outlined here. Overconsolidation would logically be very common in clay sediments although it may be too weak in fresh deposits to be easily determined.

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